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Experimental evaluation of a 20 kW oxygen enhanced self-regenerative burner operated in flameless combustion mode

Mario Sánchez, Francisco Cadavid *, Andrés Amell

Science and Technology of Gases and Rational Use of Energy Group, Faculty of Engineering, University of Antioquia, Calle 67 Número 53 – 108, Bloque 20 – 435, Medellín, Colombia

HIGHLIGHTS

- Combination of flameless combustion, oxygen enrichment and regenerative heat recovery.
- No previous studies with enrichment up to 35% with regenerative flameless burners.
- NO_x emissions were below 5 ppm and efficiency increased 5% for enrichments of 30%.
- The energy recovery ratio of regenerators remained above 80% for all enrichments.
- Air excess and ejection pressure level must be adjusted to optimized system operation.

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ABSTRACT

Results are presented on the effects of oxygen enrichment on the performance of a flameless combustion furnace equipped with a regenerative burner. Natural gas was used as fuel (~97% CH_4) and the oxygen concentration in the combustion air was varied from 21% to 35% (volumetric percent). The influence of oxygen enrichment on temperature and species profiles, pollutant emissions, thermal efficiency and regenerators effectiveness was quantified; measures were registered under steady state conditions for average wall temperatures of 880 °C. The results showed that for all oxygen enrichment rates it was possible to obtain the flameless combustion phenomena with its typical features, like no luminous effect, wide reaction zone and uniform temperature profile. A temperature peak of 1034 °C was measured for the operation with oxygen enriched air (35% O_2) compared to 975 °C when normal air (21% O_2) was used. NO_x emissions were below 5 ppm and the global efficiency increased almost 5% for an oxygen enriched level of 30%. Some comparisons to the burner operating without oxygen enrichment in conventional and flameless mode are presented to highlight the advantages of oxygen enhanced flameless combustion (OEFC) using self-regenerative burners.

1. Introduction

Flameless combustion is a promising combustion technology capable of accomplishing high efficiency and low emissions, mainly NO_x emissions, which has been a major issue in designing combustion systems, since NO_x plays a key role in acid rain formation and the generation of photochemical smog [1]. Flameless combustion is based on mix fuel and oxidizer jets with flue gas before chemical reactions take place. This is achieve by high momentum jets of fuel and oxidizer which entrain the flue gas through internal recirculation, thus diluting the oxygen concentration in the combustion zone [2].

Although flameless combustion is a relatively novel combustion technique, it has been used in different applications like heat treating and heating furnaces in steel industry, biogas burners, burners for hydrogen reformers and even stationary gas turbines. As an example in gas turbines have been achieve very low NO_x emissions as low as 1 ppm and CO emissions as low as 8 ppm [3–5].

On the other hand, the use of oxygen enhanced combustion provides several advantages on the operation of industrial furnaces, as an increased productivity, higher thermal efficiencies, greater turndown of the burners and flame stability, better ignition and flame shape control, lower exhaust gases flow rates and more compact equipment design [6]. Systems that use oxygen enriched air have greater productivity due to the higher in-furnace gas temperatures and to the higher CO_2 and H_2O concentrations in combustion products that increase the incident radiant heat flux to the processing material; additionally the smaller quantity of nitrogen in air reduces the amount of fumes in chimney and thus the energy losses to ambient, and increases the viability to perform CO_2 capture processes [7].

* Corresponding author. Tel.: +57 4 2198548; fax: +57 4 2119028.
E-mail address: fcadavid@udea.edu.co (F. Cadavid).

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Despite oxygen has many advantages, producing oxygen in traditional way is costly, then currently there are some new technologies like polymer membranes to produce oxygen enriched air in a cheaper way [8]. Also, oxygen enrichment may cause some adverse effects on furnaces operation, like damages to the refractory material, non-uniform heating and NO_x emissions increase. To overcome these adverse effects, a novel combustion technology combining the advantages of flameless combustion and oxygen enrichment has been developed. Some of the studies and technological developments in the field of oxygen enhanced flameless combustion are: the research carried out by Krishnamurthy et al. [9,10] with the commercial burners Regemat® using oxygen enrichment rates up to 29% and Rebox® using pure oxygen as oxidizer, where a comparison between a flameless regenerative burner and flameless oxy-fuel burner was performed. During the experiments, both burners exhibit uniform temperature profiles with temperature peaks below the ones obtained with conventional combustion. Radiant heat flux was higher and more uniform for flameless oxy-fuel combustion than for conventional combustion without oxygen enrichment. NO_x emissions for both burners remained very low and presented little dependence to ambient air infiltrations for the Rebox burner.

The Centre for Advance Gas Combustion Technology and the Canadian Gas Research Institute (CAGCT) [11] conducted a study where a prototype burner with a nominal firing rate of 353 kW was tested using oxygen concentration on air from 21% to 100%. In this work, were found energy savings of 40% when using pure oxygen as oxidizer. NO_x emissions increased mildly when the oxygen concentrations in combustion air was raised up to 60%, for higher O_2 concentrations the NO_x emissions started to decrease, values of 12 mg/MJ at 3% oxygen in chimney were registered. Wall temperature standard deviation changed from 19–27 °C for conventional air (21% O_2) to 31–34 °C for oxygen enrichments rates of 90%.

Also other different works are: the study developed by Praxair using burners for glass melting and steel furnaces combining pure oxygen as oxidizer with high flue gas internal recirculation [12,13], which show an increase between 15% and 30% in steel and glass production, and a reduction close to 90% in NO_x emissions; the steel reheating furnace and the aluminium melting furnace using enrichment levels between 35% and 50% O_2 for low NO_x production developed by Air Products and Chemicals [14,15]; the metals heat treating prototype furnace developed by Atreya et al. using oxygen enrichment levels of 21%, 30%, 40% [16] and the research conducted by GDF Suez [17] where a 200 kW burner developed by NFK was tested in a semi-industrial scale facility.

None of these studies have used oxygen enrichment rates up to 35% with self-regenerative flameless burners. Additionally the effect of oxygen enrichment on the regenerative system performance and the effect of the ejection level on combustion stability were not studied either. Then, in the present work the fundamental behavior of a 20 kW prototype self-regenerative burner at Antioquia University is presented. The experimental campaign has been carried out combining flameless combustion, regenerative heat recovery and oxygen enrichment with rates of 21%, 25%, 30% and 35% O_2.

2. Methods

2.1. Experimental facility

The regenerative flameless combustion furnace developed by the Science and Technology of Gases and Rational Use of Energy Group (GASURE) has four main components: burner, combustion chamber, auxiliary and control modules. The furnace is a combustion chamber lined with ceramic blanket with a cross section of 600 mm × 600 mm and a length of 1350 mm, it incorporates four steel tubes that work as a counter-flow heat exchanger to emulate a heat sink, using air as working fluid. The furnace has two windows and a lateral door for the observation and photographical record of the flameless combustion phenomenon. Ni-Cr K type thermocouples mounted flush to the insulation modules in the furnace top wall allow the measurements of wall temperatures, see Fig. 1. The back wall has three orifices to insert probes for measuring temperature and species in the horizontal middle plane of the combustion chamber.

The burner has central triple cannon to supply the fuel for flameless and conventional mode, and to supply a co-flow of combustion air for flame mode. During the flameless mode the burner injects fuel at high velocity through a central nozzle and uses four peripheral nozzles to extract combustion products and to inject combustion air, and the burner has not swirling production device. The air is injected at high velocity into the combustion chamber through a pair of nozzles; meanwhile, the other two nozzles extract exhaust gases from the combustion chamber preheating the regenerators. The burner injects air and extracts gases in time cycles of 30 s, which is called the "switching time". After that switching time, the air nozzles switch to extraction mode and the extraction nozzles switch to air injection mode. During this cyclic process, the fuel continuously flows through the central nozzle. Four ducts house the cordierite honeycombs regenerators that enable the preheating of the combustion air and the energy recovery from the combustion products. To ensure that combustion process was completed, the species were measured after the extracting combustion nozzles and it was observed that species concentration in this place correspond to the equilibrium state.

The high velocity and separate injection of air and fuel into the combustion chamber promotes the recirculation of a large quantity of combustion products, achieving low oxygen concentration reaction zones with temperatures above the self-ignition temperature of the fuel, resulting in wide reaction zones with uniform temperature profiles and without the presence of a visible flame front.

All the auxiliary devices as the air supply fan, control elements for air, fuel and oxygen, the ejection system and the four-way valve are located in the auxiliary module. The ejection system is used to produce the vacuum that makes possible the extraction of the combustion products through the honeycombs, and the four-way valve is used to switch the air flow between the two pairs of peripheral nozzles. Hot wire flow meters were used to measure the flow rates of air, natural gas and combustion products.

2.2. Methodology

The purpose of the experimental evaluation was to assess the effect of varying the oxygen concentration of the combustion air on the performance parameters of a regenerative flameless combustion furnace. The parameters used for the assessment were the thermal efficiency of the process, the temperature profiles inside the combustion chamber, the reaction zone structure, combustion stability and pollutant emissions. Three oxygen enrichment rates were used, 25%, 30%, 35% (by volume) and natural gas with a low heating value of 13.89 kW h/kg was used as fuel ($\sim$97% CH_4– volumetric percent) with a constant thermal input of 20 kW. Also, the oxygen concentration in chimney was held constant around 3.2% (wet basis) for all the oxygen enrichment levels, and the wall reference temperature was held around 870 °C. Additionally, in order to highlight the advantages of oxygen enhanced flameless combustion, comparisons to the burner operating in flameless and flame mode without oxygen enrichment were carried out. No changes in air nozzles geometry were done during experiments. The experimental conditions are presented in Table 1.

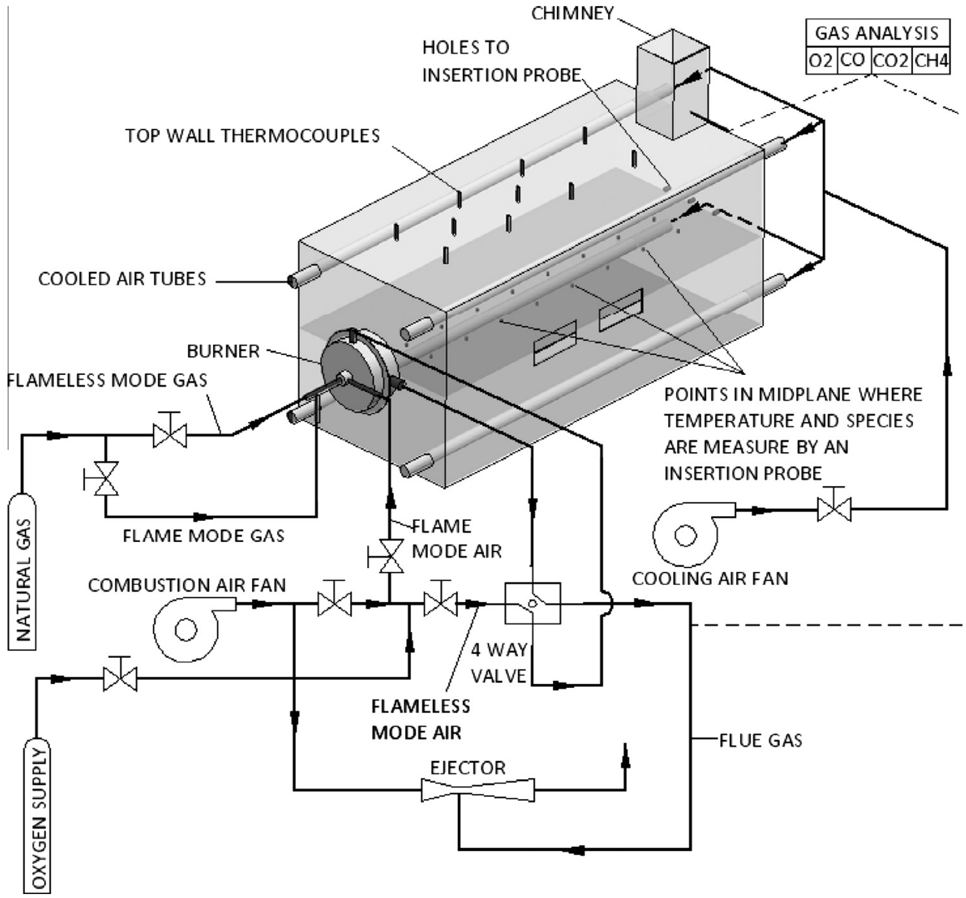

Fig. 1. Schematic representation of the regenerative flameless combustion furnace and auxiliary equipment.

Table 1
Summary of experimental conditions.

Parameter	Flame mode	Flameless mode			
Designation	O21 flame	O21	O25	O30	O35
Oxygen concentration (vol.%)	21	21	25	30	35
Thermal input (kW)	20.0	20.0	20.0	20.0	20.0
Natural gas flow rate (kg/s)	39.99×10^{-5}	39.99×10^{-5}	39.99×10^{-5}	39.99×10^{-5}	39.99×10^{-5}
Air flow rate (kg/s)	0.00822	0.00822	0.00675	0.00553	0.00469
Air preheating temperature (°C)	600.0	600.0	600.0	600.0	600.0
Excess air ratio	1.20	1.20	1.17	1.14	1.12
Oxygen in exhaust gases (vol.%) (wet basis)	3.218	3.218	3.218	3.218	3.218
Oxygen in exhaust gases (vol.%) (dry basis)	3.8	3.8	4.0	4.2	4.4

Temperatures in the top wall of the furnace were measured by ten thermocouples located flush to the insulation while temperature and species profiles in the middle plane of the combustion chamber were registered every 15 cm from the back wall of the chamber (opposite to the burner) by an insertion probe, which was introduced into the combustion chamber through the three horizontal orifices located in this wall. As the burner operates in a cyclic process, switching the air injection and gases extraction between the two pairs of nozzles, the process is considered to work in pseudo-steady conditions. For these reason the temperature measurements correspond to the highest value registered at each location during each cycle. Similarly, the species concentration in the middle plane of the combustion chamber was measured at the end of the injection cycle of the horizontal nozzles. All measures were carried out under pseudo-steady state conditions for a reference temperature of 870 ± 10 °C. To measure the species profile a water-cooled sampling probe with a sonic neck was used, the sonic neck allows an instant cooling of the combustion products stopping the oxidation reactions, guarantying an exact measure of the species concentration in the sampling point. The probe was connected to a gas analyzer with a non-dispersive infrared (NDIR) sensor for CH_4 (0–100%), CO_2 (0–40%) and CO (0–60.000 ppm). O_2 (0–100%) measurements were carried out with a sensor that uses the paramagnetic principle. NO_x (0–100 ppm) emissions were measured using the chemiluminescence technique, which accuracy is ±1 ppm.

When the furnace switched from the conventional mode to the flameless combustion regime, the ejection system was modulated to ensure a proper exhaust gas recirculation ratio and to maximize the amount of combustion products ejected through the regenerators, in order to increase the thermal efficiency of the furnace. Around 75% of the exhaust gases were evacuated through the regenerators, whilst the remainder was exhausted through the main chimney. Special attention was taken to avoid negative

pressure inside the combustion chamber since it would generate that air entering from the chimney, which increase the oxygen concentration in the reaction zone causing an increase in temperature peaks and therefore in NO_x emissions. Additionally very high exhaust gas recirculation ratios could destabilize the flameless combustion regime producing a raise in CO emissions, especially during the switching between nozzles [18].

3. Results and discussions

3.1. Thermal fields

In order to compare temperature profiles inside the combustion chamber for the different oxygen enrichment levels the following parameters were used: maximum temperature peak, average and standard deviation of temperature in the middle plane and in the top wall of the combustion chamber. Fig. 2 presents the experimental temperature contours in the middle plane of the combustion chamber. It can be observed a very uniform temperature profile of the flameless combustion regime with and without oxygen enrichment when compare to the conventional combustion regime. Near to the burner ports the temperatures of conventional combustion were even higher than those obtained with 35% oxygen enrichment in the flameless mode.

According to expectations, temperatures in the middle plane of the combustion chamber increased when the oxygen concentration in the combustion air was increased, however for the 35% oxygen enrichment level, the increase in peak temperature was below 60 °C; this confirms the highly uniform temperature profile of the flameless combustion regime even when oxygen enriched air is used. The behavior of temperature profiles can be explained by the following reasons: higher oxygen concentration in the reaction zone, lower mass-flow of recirculated combustion products flowing into the reaction zone that could cool down the reactions and lower turbulent mixing intensity that causes the appearance of species and temperature gradients.

Oxygen enrichment rates of 35% produce a reduction of 43% of the mass-flow rate of combustion air and a reduction of the air jet velocity from 59 m/s to 33 m/s, this condition affects the mixing of the reactants and produces the appearance of greater temperature gradients in the combustion chamber. Despite the reduction in air

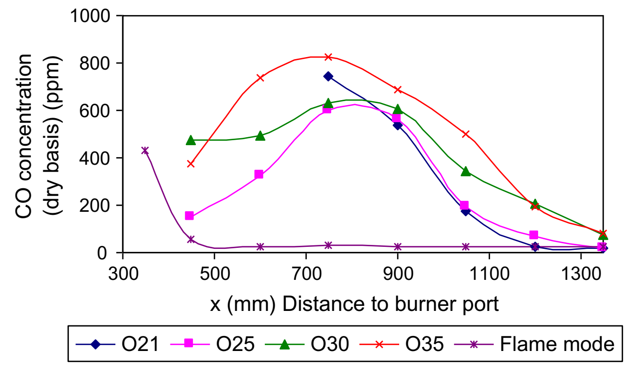

Fig. 3a. CO concentration profiles (on dry basis) along the central axis of the combustion chamber for different oxygen enrichment rates.

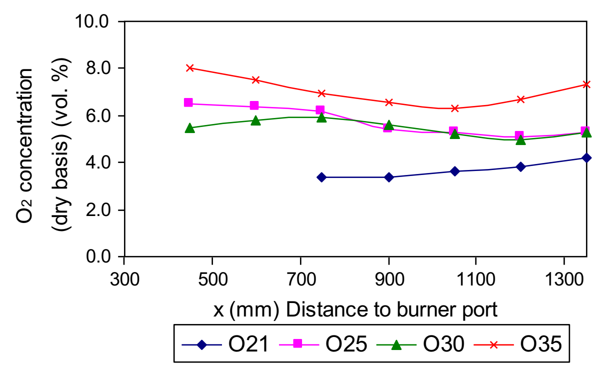

Fig. 3b. O_2 concentration profiles (on dry basis) along the central axis of the combustion chamber for different oxygen enrichment rates.

jet velocity, the exhaust gas recirculation ratio, defined by Wünning and Wünning [19], was the appropriate to maintain very low oxygen concentrations within the reaction zone, avoiding the occurrence of excessive temperature gradients, as shown in Fig. 3b.

Table 2 shows a summary of the maximum, average and standard deviation of temperature for the middle plane, central axis and top wall of the combustion chamber. The measurements

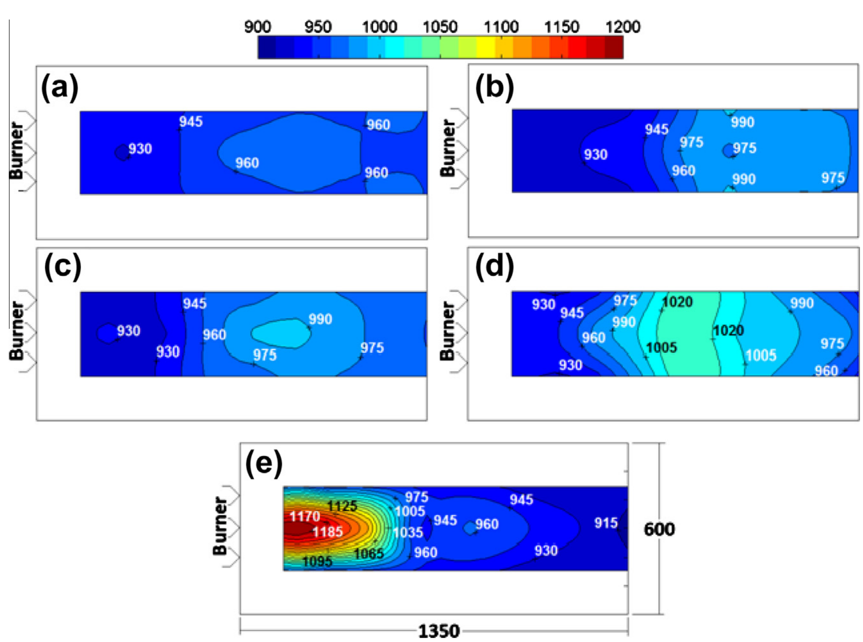

Fig. 2. Experimental temperature contours in the middle plane of the combustion chamber (°C): (a) 21% O_2, (b) 25% O_2, (c) 30% O_2, (d) 35% O_2 and (e) 21% O_2 flame mode.

Table 2
Maximum, average and standard deviation of temperature for central axis, middle plane and top wall of the combustion chamber.

Location	Criterion	Oxygen concentration on air				
		O21Flame	O21	O25	O30	O35
Central Axis	T_{max}	1195	975	980	992	1034
	$T_{average}$	1014	953	957	961	986
	$T_{deviation}$	114	17	24	26	31
Middle plane	T_{max}	1195	975	992	992	1034
	$T_{average}$	976	951	955	958	978
	$T_{deviation}$	88	14	25	24	34
Top wall	T_{max}	–	929	923	928	939
	$T_{average}$	–	874	889	892	902
	$T_{deviation}$	–	37	25	25	27

presented in the Table 2 were carried out with the burner operating in flame mode with 21% O_2 and in flameless mode with oxygen enrichments of 21%, 25%, 30% and 35% O_2. Although both conditions, O21 flame and O21, have the same oxygen concentration in oxidizer, they are different because in condition O21 flame, the oxidizer is injected into the combustion chamber in a way such as a conventional flame appears, while in condition O21 oxidizer is injected such as flameless combustion regime is achieved. It can be observed that when an oxygen concentration of 35% on combustion air was used, only an increase of 10 °C was registered for the wall peak temperature when compared to the operation with normal air. The standard deviation of temperature changed from 25 to 27 °C with respect to the operation with lower oxygen enrichment rates. In the flameless mode the standard deviation of temperature was lower for the higher oxygen enrichment levels compare to the one obtained with normal air, this was due to the better control of process temperature with the air cooling tubes during the experiments with oxygen enrichment.

3.2. Species profiles

With the measurements of species profiles along the central axis of the combustion chamber it was intended to confirm that it would be still possible, using oxygen enriched air, to obtain a detached and wide reaction zone, which is typical from flameless combustion regimes with conventional air (21% O_2). Fig. 3a shows the CO profile along the central axis of the combustion chamber for different concentrations of oxygen in the air (ranging from 21% to 35%). It can be observed that when the burner was run on the conventional flame mode most of the oxidation take place in the first 400 mm of the chamber (near the burner ports). On the other hand, for the flameless regime, at the same distance from the burner (400 mm), the CO concentration is just starting to rise; this trend indicates that for all the oxygen enrichment levels a detached reaction zone that extends over a large volume of the combustion chamber was obtained. Fig. 3b shows that despite the oxygen concentration inside the reaction zone was higher for the oxygen enrichment cases, the oxygen percent within this zone remained always below 8%, ensuring enough dilution to preserve the conditions of the flameless combustion regime for all the experimental conditions.

The maximum peak of CO tends to be located around 750 mm from the burner port for all oxygen concentrations in the air. However, as seen in Fig. 3a, as the oxygen concentration in the air increases, the reaction zone tends be longer, since the oxidation reactions cover a longer portion of the combustion chamber. As the velocity of the air jet is reduced when the oxygen enrichment is increased (as the geometry of the air ports was held constant), it leads to a reduction of the turbulent mixing intensity and therefore a delay of the mixing between fuel and air. Even though the slower mixing between air and fuel, a complete oxidation of the fuel was obtained when oxygen enriched air was used, this was due to the higher temperatures that allow higher reaction rates in the second half of the combustion chamber and to the higher residence time of unburned combustion products inside the combustion chamber during the flameless combustion regime. It is worth to mention that no changes in the burner nozzles diameters were made during the experiments. It is possible to maintain the reaction zone location or even to reduce the ignition delay under the oxygen enhanced flameless combustion regime if the air nozzles diameters are reduced and a higher air supply pressure is used.

Table 3
Composition by volume (on dry basis) of combustion products in chimney for the different oxygen enrichment rates for operation in flameless combustion regime.

Oxygen enrichment level (vol.%)	Volumetric composition of species in exhaust gases			
	O_2 (vol.%)	CO_2 (vol.%)	CO (ppm)	NO_x (ppm)
21	3.4	9.84	15	3
25	2.8	12.35	15	2
30	3.0	15.38	13	2
35	4.4	17.63	21	2

3.3. Emissions

Table 3 shows the volumetric composition on a dry basis of the combustion products in chimney for the different oxygen enrichment rates used during the experiments. As expected, the CO_2 concentration in combustion products increases when the oxygen enrichment level is increased and at the same time the concentration in chimney is held constant. The air and oxygen supplies were adjusted during experiments to maintain an oxygen concentration in chimney around 3.2% (wet basis); Table 3 shows that a precise control of air excess was not obtained for 25% and 30% oxygen concentration in the air, due to problems with the accuracy of the butterfly valve that controls air flow rate.

Table 3 shows that CO and NO_x emissions were very low for all the oxygen enrichment levels, below 25 ppm and 5 ppm respectively. The ejection system was adjusted to avoid the increase of CO emissions that appears when very high recirculation ratios are used [18]. The flow rate of enriched air was controlled to ensure an optimal air excess avoiding the increase of oxygen concentration inside the reaction zone that could trigger temperature gradients, the appearance of unstable lifted conventional flames and therefore thermal NO_x emissions. On the other hand, an increase of CO emissions also appears when the recirculation ratio exceeds the value required to dilute the reactants mixture up to optimal values, leading on the contrary to an excessive cooling of the reaction zone [18], causing a reduction in the concentration of OH radicals that control the CO–CO_2 conversion [20]. During the experiments, the ejection system was modulated to evacuate approximately 75% of combustion products through the regenerators.

Regarding nitrogen oxide emissions, most NO_x is formed trough the thermal route in the fraction of a second when the flame temperature reaches a peak between 1 538 °C and 1 760 °C. Due to the low process temperature and to the high internal flue gas recirculation ratio used during the flameless combustion mode, temperature peaks were hardly found in the range just mentioned. Additionally, in the flameless regime, turbulent fluctuations of oxygen concentration as well as free radical formation are inherently limited, avoiding in this way the production of NO_x trough the prompt route.

3.4. Regenerative system performance

It was intended to establish if the reduction in mass flow rate and the changes in composition of the combustion air and exhaust gases would affect the performance of the regenerative system. Thermocouples located at the inlet and outlet of the regenerator

registered the air and combustion products temperatures when they entered and left the honeycombs. The measures were taken under pseudo-steady state conditions at the end of each cycle, when the amount of energy stored in the regenerators remained constant and the outlet temperature of exhaust gases and the pre-heating temperature of air remained also constant.

Figs. 4a and 4b shows the temperature evolution of the hot and cold side of the regenerators during four switching cycles, using an oxygen concentration in the air of 25%. Lower temperature peaks in Fig. 4a represent the air inlet temperature to the regenerator, while higher peaks represent the exhaust gases outlet temperature after crossing the regenerator. In Fig. 4b lower peaks correspond to the air preheating temperature, while higher temperature peaks correspond to the combustion products inlet temperature to the honeycombs. The recorded temperature at hot and cold sides were corrected according to the thermocouple time response, because of the short switching time used in regenerative burner that makes impossible to register in real time the real values of temperature of the air and combustion products. The temperature corrections were done according to the procedure followed by Rafidi et al. [21].

To assess the effect of oxygen enrichment on the regenerative system performance, the thermal effectiveness and energy recovery ratio (ERR) parameters were calculated. ERR indicates how much of the energy carried by the combustion products is used to preheat combustion air. On the other hand, thermal effectiveness is useful to compare the performance of the regenerators with other types of heat recovery systems. Thermal effectiveness compares the maximum possible amount of energy that a heat exchanger can recover with the real amount of energy recovered during its operation [21].

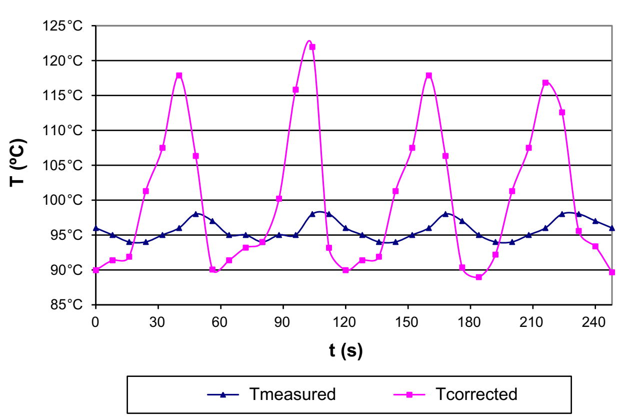

Fig. 4a. Evolution of temperature profiles for the cold side of the regenerative system for an oxygen concentration on air of 25%.

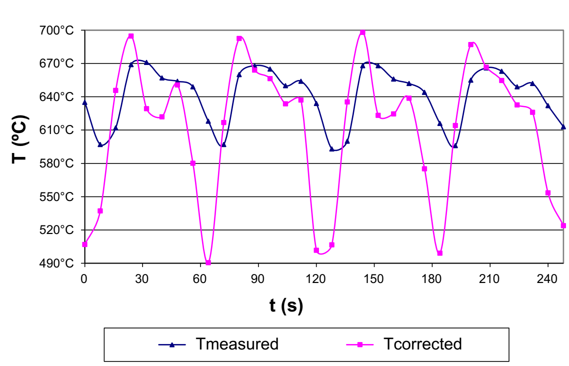

Fig. 4b. Evolution of temperature profiles for the hot side of the regenerative system for an oxygen concentration on air of 25%.

Table 4
Performance parameters of the regenerative system for different oxygen enrichment rates.

Oxygen enrichment level (vol. %)	Ejection ratio (%)	ε_a (%)	ε_g (%)	TRE (%)	ΔP_{iny} (Pa)	ΔP_{eye} (Pa)
25	69.3	92.3	94.8	82.0	280	180
30	75.4	94.5	93.6	81.7	240	180
35	70.4	94.8	94.2	83.4	200	120

Table 5
Energy Balances.

	Enrichment level				
	O21-Flame	O21	O25	O30	O35
Fuel (%)	95.0	93.0	90.4	89.8	90.0
Combustion air + cooling air (%)	5.0	7.0	9.6	10.2	10.0
Chimney losses (%)	39.2	6.5	8.6	5.8	6.2
Ejected gases losses (%)	0.0	6.4	1.9	1.8	1.5
Wall losses	18.8	14.4	17.9	17.7	17.8
Useful energy (%)	41.5	70.1	71.7	74.7	74.4

Table 4 summarizes the measured values for the performance parameters of the regenerative system during the experiments. It is important to highlight that when the regenerators reach steady state conditions, the cold and hot side effectiveness match with each other, because the temperature of the ceramic matrix at the end of the cycle remain constant and there is no energy accumulation in time. A comparison of the hot and cold air side effectiveness values allows us to confirm if the system has reached steady state conditions.

Results showed that for all oxygen enrichment rates the performance of the regenerative system was not significantly affected, as the energy recovery ratio remained above 80% for all cases and around 70–75% of the combustion products were ejected trough the honeycomb regenerators. Despite the reduction in the combustion products mass flow rate that lowers the convective coefficient of heat transfer, the increase of the residence time of the products throughout the honeycombs avoided a reduction in the performance of the regenerators. On the other hand, as expected, pressure drop along the regenerators decreases with oxygen enrichment due to a lower mass flow rate of air and combustion products. The pressure drop for the oxygen enrichment levels of 25% and 30% were the same because the ejection ratio was higher for the 30% oxygen enrichment level.

3.5. Energy balances

Table 5 presents energy balances for the furnace operating in flame and flameless mode with and without oxygen enrichment. Chemical energy of the fuel and sensible energy from combustion air and cooling air are counted as inlets, whereas the energy losses through the chimney and walls, the energy absorbed by the cooling air and the remainder sensible energy of combustion products after leaving the regenerators are counted as outlets. To calculate energy wall losses, was supposed an external heat transfer coefficient of 8 W/m^2 K, and a room temperature of 25 °C.

Table 5 shows an important increase of the efficiency in the flameless mode in comparison to the operation of the furnace in conventional mode where the energy recovery system was not used. For the burner operation in flame mode without energy recovery the useful energy was only 41.0%, whereas in flameless mode, for all oxygen concentrations in the air, the useful energy

was above 70.0%. The efficiency is also affected in the flameless combustion regime because of the wider reaction zone and the more uniform temperature profiles that causes an increase in the incident radiant heat flux to the load.

Even though oxygen enrichment increases thermal efficiency of the process, the increased was not higher due to the presence of the regenerative system that held sensible energy losses in chimney at minimum for all cases. Additionally, the higher energy losses through walls during experiments with oxygen enriched air prevented the achievement of higher efficiencies. Despite these facts, a regenerative burner using oxygen enriched air may overcome oxygen costs if a low cost oxygen production system is installed and if other of its advantages are considered, such as the increasing of the productivity and the lower cost of fumes post-treatment. It is important to highlight that the efficiency was higher for the oxygen enrichment level of 30.0%, thanks to the higher mass flow of gases extracted trough the regenerators and to the lower air excess used at this enrichment level.

4. Conclusions

- It was possible to obtain the flameless combustion regime using oxygen concentrations in the air up to 35% with a 20 kW self-regenerative burner. However, to run the system at its optimal point, it is necessary to adjust the air excess and the ejection pressure level. In the present work, an oxygen concentration in chimney of 3.2% (wet basis) was used, and around 75% of the exhaust gases were ejected through the regenerators for all enrichment rates. No changes in the geometry of the air or fuel nozzles were necessary.
- Even for oxygen concentrations levels of 35% in the combustion air, the reaction zone was wide and detached from the burner port; the CO peak wa_s located around 750 mm from the burner port for all oxygen enrichment levels. Nevertheless, as the oxygen enrichment level was raised, there was a tendency to an increase in the reaction zone length, due to a reduction of the air injection velocity and hence in turbulent mixing. Regarding pollutant emissions, CO and NO_x emissions were below 25 ppm and 5 ppm respectively. A temperature increase of only 59 °C was registered for the peak temperature inside the combustion.
- The performance of the regenerative system was not significantly affected by oxygen enrichment; when the ratio of exhaust gases evacuated through the regenerators was 70–75% the energy recovery ratio of the honeycombs was above 80% for all oxygen enrichment rates. This characteristic, along with the lower energy losses in chimney and the higher heat flux from the reaction zone, allowed an increase of 5% in the furnace efficiency when the oxygen concentration i_n the air was 30%.

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